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METHOD AND APPARATUS FOR FACILITATING MAP DATA PROCESSING FOR INDUSTRIAL VEHICLE NAVIGATION

(75)

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5,568,030 A

10/1996

Nishikawa et al.

5,612,883 A

3/1997

Shaffer et al.

5,646,845 A

7/1997

Gudat et al.

5,682,317 A

10/1997

Keeler et al.

5,916,285 A

6/1999

Alofs et al.

5,961,571 A

10/1999

Gorr et al.

6,012,003 A

1/2000

Astrom

6,092,010 A

7/2000

Alofs et al.

6,208,916 B1

3/2001

Hori

6,246,930 B1

6/2001

Hori

6,308,118 B1

10/2001

Holmquist

6,539,294 B1

3/2003

Kageyama

6,592,488 B2

7/2003

Gassmann

6,917,839 B2 *

7/2005

Bickford 700/30

(Continued)

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(56)

References Cited

U.S. PATENT DOCUMENTS

4,855,915 A	8/1989	Dallaire	
4,858,132 A	8/1989	Holmquist	
5,011,358 A	4/1991	Andersen et al.	
5,051,906 A	9/1991	Evans, Jr. et al.	
5,170,352 A	12/1992	McTamaney et al.	
5,202,832 A *	4/1993	Lisy 701/24	
5,471,393 A	11/1995	Bolger	
5,491,670 A	2/1996	Weber	
5,539,638 A	7/1996	Keeler et al.	

FOREIGN PATENT DOCUMENTS

DE	19757333 C1	9/1999
DE	10220936 A1 *	12/2003

(Continued)

OTHER PUBLICATIONS

International Search Report and Written Opinion mailed Oct. 31, 2012 for PCT/NZ2012/000091.

(Continued)

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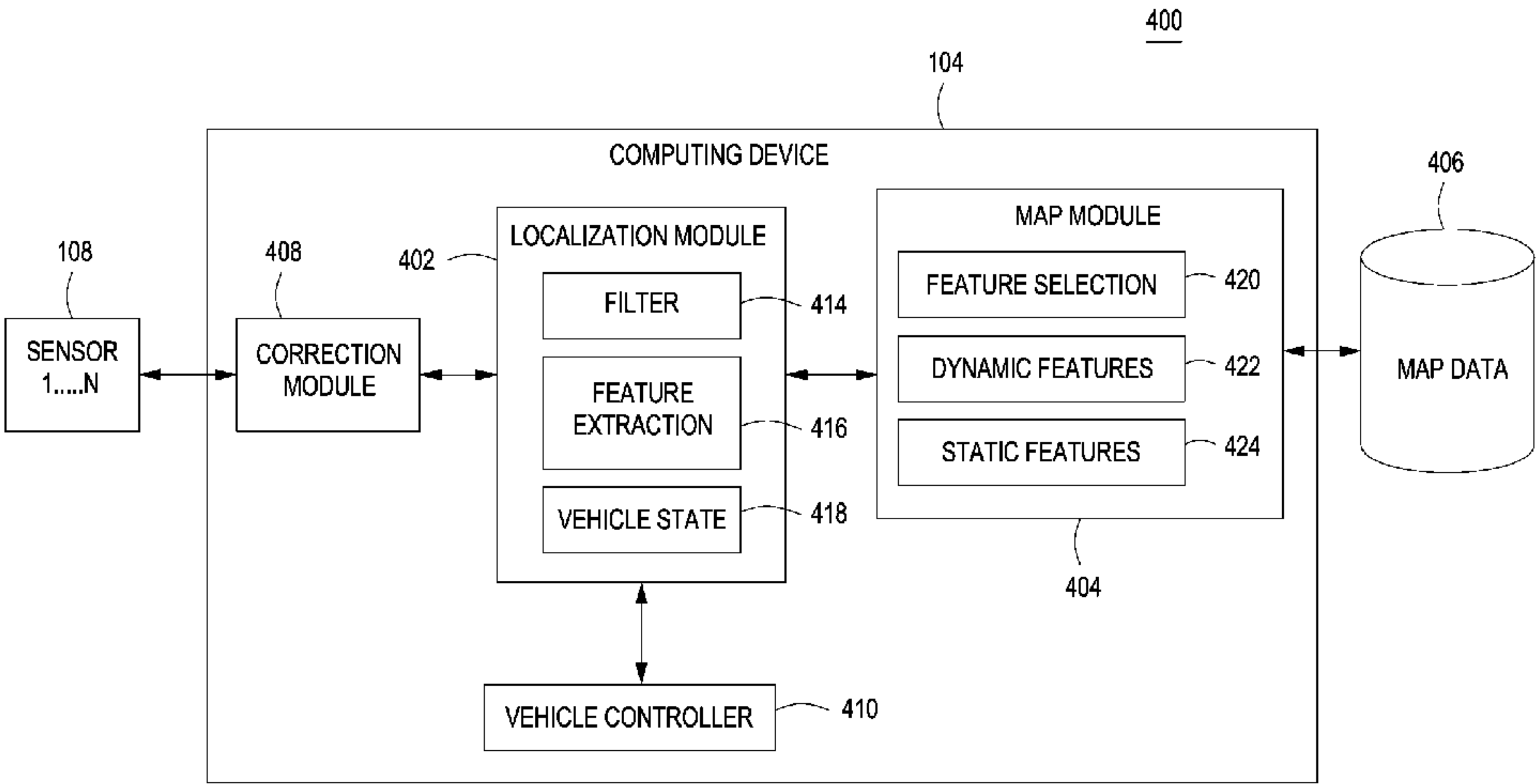
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(57)

ABSTRACT

A method and apparatus for facilitating map data processing for industrial vehicle navigation is described. In one embodiment, the method of partitioning map data for industrial vehicle navigation includes segmenting map data associated with a physical environment into a plurality of sub-area maps, identifying a sub-area map that corresponds with a current vehicle location and navigating an industrial vehicle using the identified sub-area map.

14 Claims, 9 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

6,952,488	B2	10/2005	Kelly et al.	
7,148,458	B2	12/2006	Schell et al.	
7,162,338	B2	1/2007	Goncalves et al.	
7,177,737	B2	2/2007	Karlsson et al.	
7,272,467	B2	9/2007	Goncalves et al.	
7,539,563	B2	5/2009	Yang et al.	
7,646,336	B2	1/2010	Tan et al.	
7,679,532	B2	3/2010	Karlsson et al.	
7,688,225	B1	3/2010	Haynes et al.	
7,689,321	B2	3/2010	Karlsson	
7,720,554	B2	5/2010	DiBernardo et al.	
7,734,385	B2	6/2010	Yang et al.	
7,844,364	B2	11/2010	McLurkin et al.	
7,996,097	B2	8/2011	DiBernardo et al.	
8,020,657	B2	9/2011	Allard et al.	
8,050,863	B2	11/2011	Trepagnier et al.	
8,103,383	B2	1/2012	Nakamura	
8,126,642	B2	2/2012	Trepagnier et al.	
8,150,650	B2	4/2012	Goncalves et al.	
8,204,679	B2	6/2012	Nakamura	
8,255,107	B2	8/2012	Yang et al.	
8,280,623	B2	10/2012	Trepagnier et al.	
2004/0030493	A1 *	2/2004	Pechatnikov et al.	701/208
2004/0202351	A1	10/2004	Park et al.	
2004/0249504	A1	12/2004	Gutmann et al.	
2005/0149256	A1 *	7/2005	Lawitzky et al.	701/207
2005/0182518	A1	8/2005	Karlsson	
2006/0181391	A1	8/2006	McNeill et al.	
2006/0184013	A1	8/2006	Emanuel et al.	
2007/0061043	A1 *	3/2007	Ermakov et al.	700/263
2007/0090973	A1	4/2007	Karlsson et al.	
2007/0106465	A1	5/2007	Adam et al.	
2007/0150097	A1	6/2007	Chae et al.	
2007/0153802	A1	7/2007	Anke et al.	
2007/0262884	A1	11/2007	Goncalves et al.	
2009/0140887	A1	6/2009	Breed et al.	
2009/0216438	A1	8/2009	Shafer	
2010/0161224	A1	6/2010	Lee et al.	
2010/0222925	A1	9/2010	Anezaki	
2010/0256908	A1	10/2010	Shimshoni et al.	
2010/0268697	A1	10/2010	Karlsson et al.	
2011/0010023	A1	1/2011	Kunzig et al.	
2011/0121068	A1	5/2011	Emanuel et al.	
2011/0125323	A1	5/2011	Gutmann et al.	
2011/0150348	A1	6/2011	Anderson	
2011/0153338	A1	6/2011	Anderson	
2011/0230207	A1	9/2011	Hasegawa	
2012/0035797	A1	2/2012	Oobayashi et al.	
2012/0101784	A1	4/2012	Lindores et al.	
2012/0191272	A1	7/2012	Andersen et al.	
2012/0323431	A1 *	12/2012	Wong et al.	701/25
2013/0006420	A1	1/2013	Karlsson et al.	

FOREIGN PATENT DOCUMENTS

DE	10234730	A1 *	2/2004
DE	102007021693	A1	11/2008
EP	1732247	A1	12/2006
GB	2389947	A	12/2003
JP	60067818	A	4/1985
JP	2002048579	A	2/2002
JP	2002108446	A	4/2002
JP	2005114546	A	4/2005
WO	03096052	A2	11/2003

OTHER PUBLICATIONS

Borenstein et al. "Mobile Robot Positioning—Sensors and Techniques", Journal of Robotic Systems, Special Issue on Mobile Robots, vol. 14, No. 4, pp. 231-249, Apr. 1997.

Harmon et al., "A Technique for Coordinating Autonomous Robots", Autonomous Systems Branch Naval Ocean Systems Center San Diego, CA 92152, 1986.

Jansfelt et al., "Laser Based Position Acquisition and Tracking in an Indoor Environment", Proc. Int. Symp. Robotics and Automation, 1998.

Siadat et al., "An Optimized Segmentation Method for a 2D Laser-Scanner Applied to Mobile Robot Navigation", Proceedings of the 3rd IFAC Sympo9sium on Intelligent Components and Instruments for Control Applications, 1997.

International Search Report and Written Opinion pertaining to International Patent Application No. PCT/NZ2012/000084, dated Jan. 30, 2013.

Search Report/Written Opinion from PCT/NZ2012/000051 mailed Jan. 2, 2013.

Search Report/Written Opinion from PCT/US2012/054062 mailed Nov. 27, 2012.

Search Report/Written Opinion from PCT/US2012/052247 mailed Nov. 27, 2012.

Office Action from U.S. Appl. No. 12/948,358 mailed Apr. 8, 2013.

Office Action from U.S. Ser. No. 660,616 mailed Nov. 27, 2013.

"Three Engineers, Hundreds of Robots, One Warehouse," Guizzo, IEEE Spectrum, Jul. 2008.

Office Action from U.S. Appl. No. 13/116,600 mailed Dec. 31, 2012.

Office Action mailed May 8, 2013 from U.S. Appl. No. 13/672,260, filed Nov. 8, 2012.

Office Action mailed May 21, 2013 from U.S. Appl. No. 12/718,620, filed Mar. 5, 2010.

Office Action mailed Jul. 12, 2013 from U.S. Appl. No. 13/227,165, filed Sep. 7, 2011.

Office Action pertaining to U.S. Appl. No. 13/159,500, dated Mar. 26, 2013.

Office Action pertaining to U.S. Appl. No. 13/219,271, dated Feb. 25, 2013.

Office Action pertaining to U.S. Appl. No. 13/153,743, dated Mar. 4, 2013.

* cited by examiner

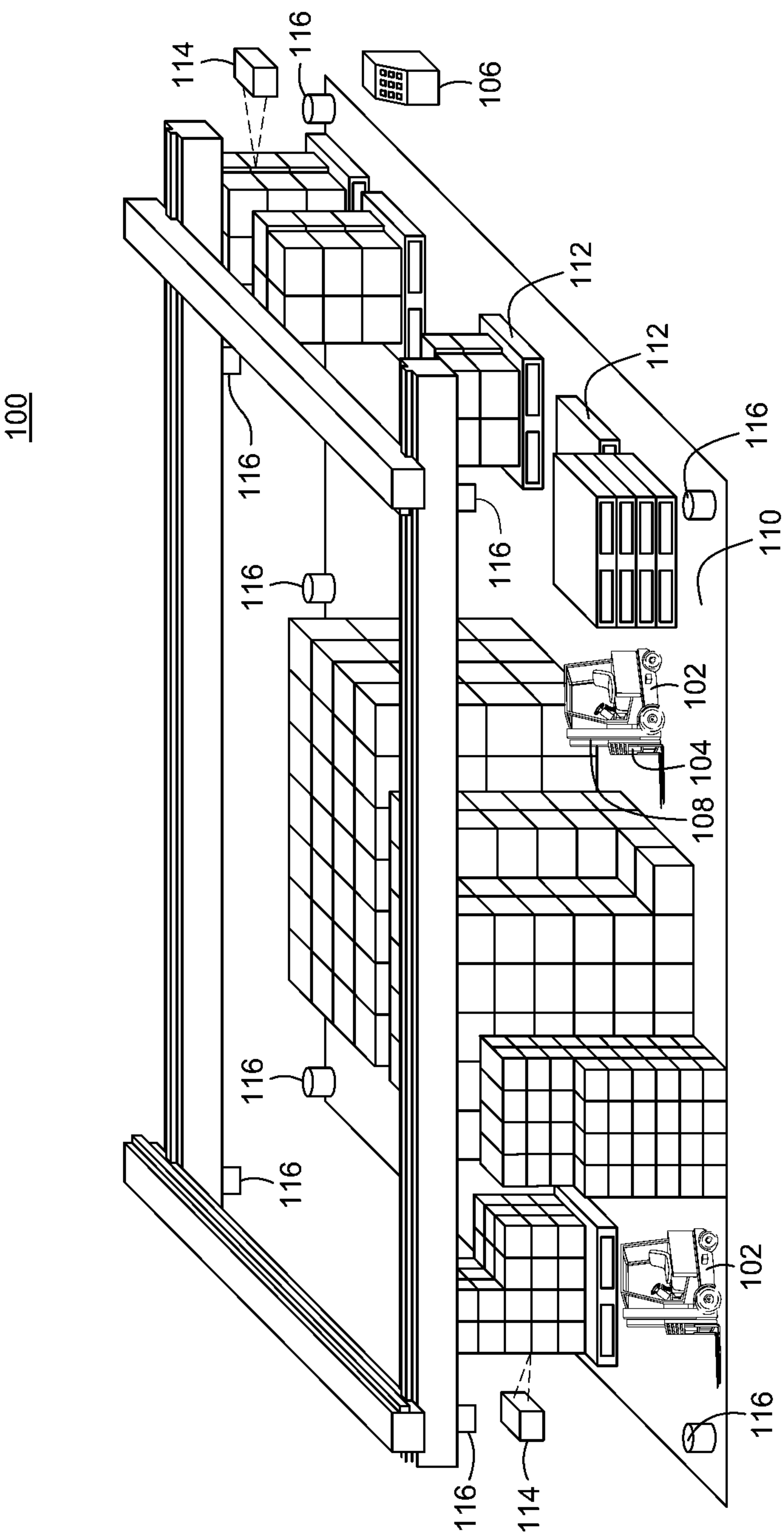


FIG. 1

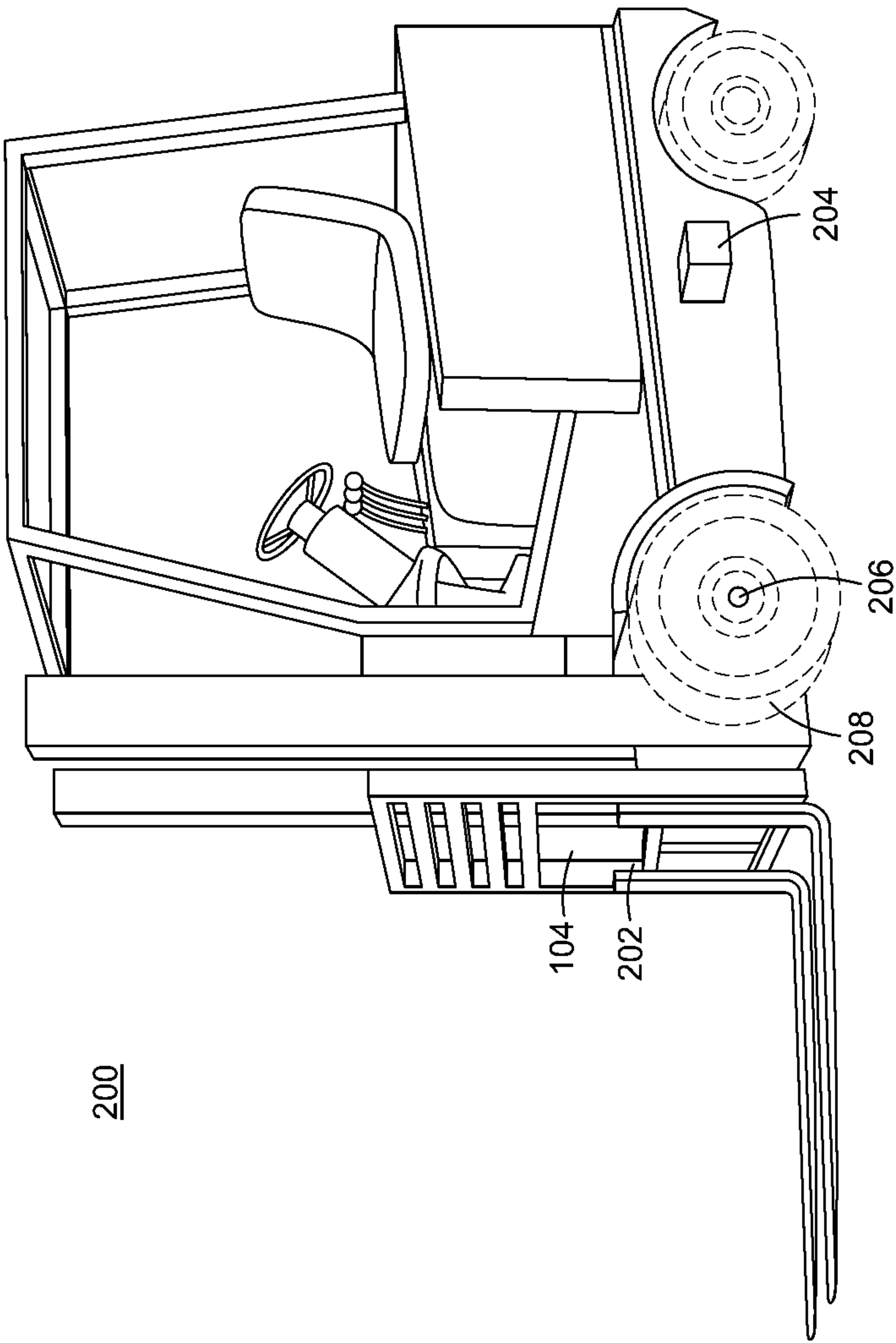


FIG. 2

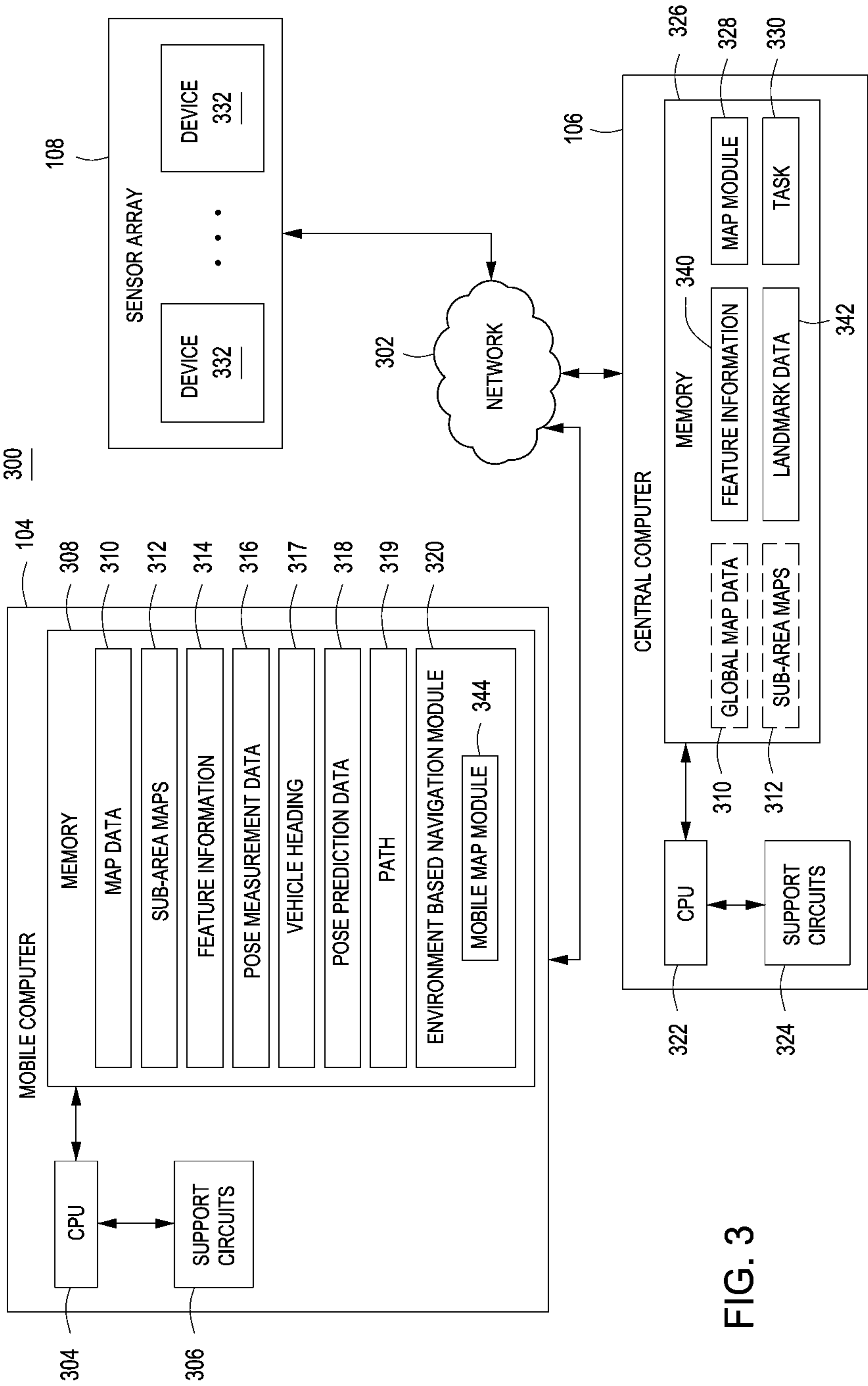


FIG. 3

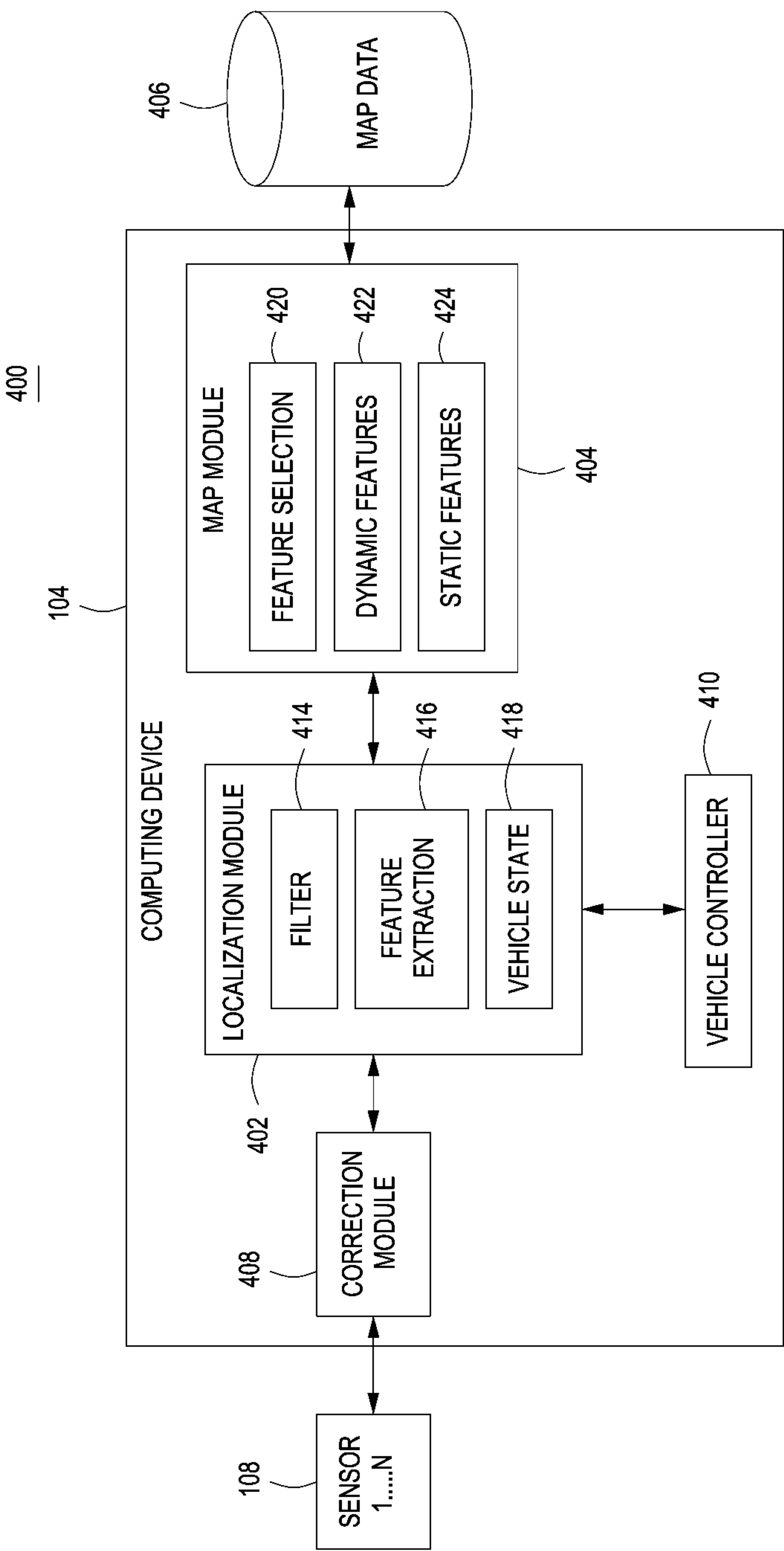
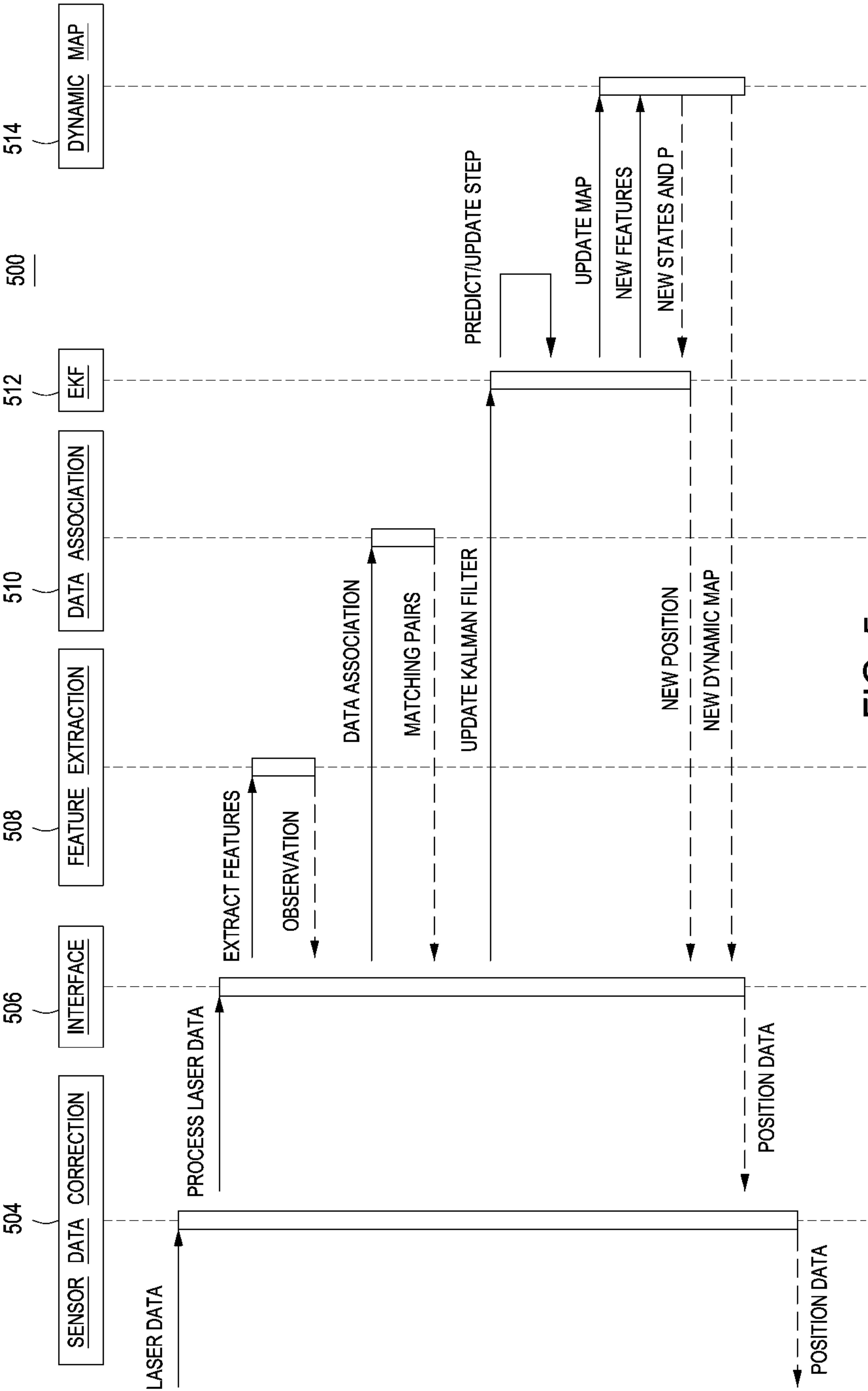


FIG. 4



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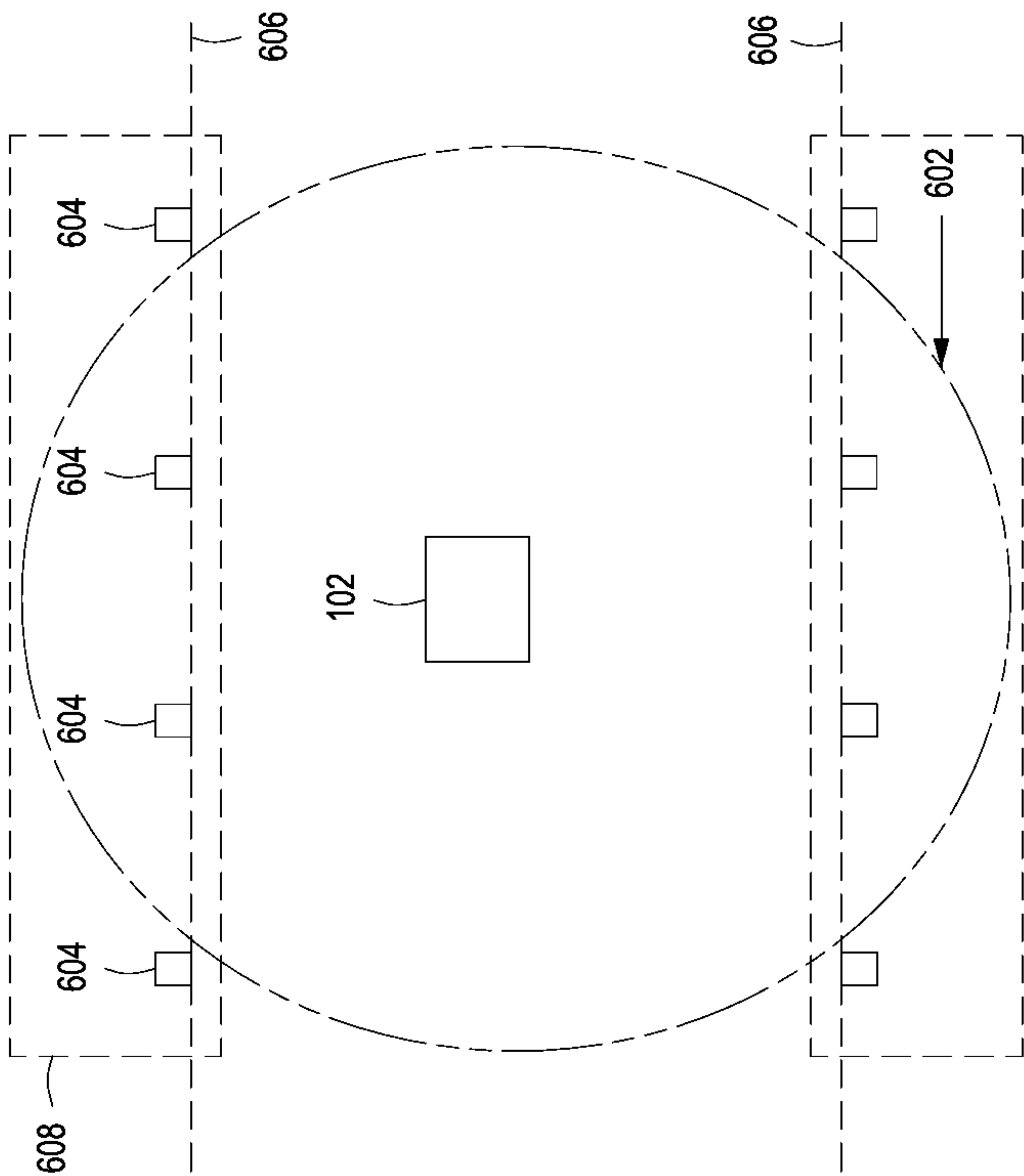


FIG. 6

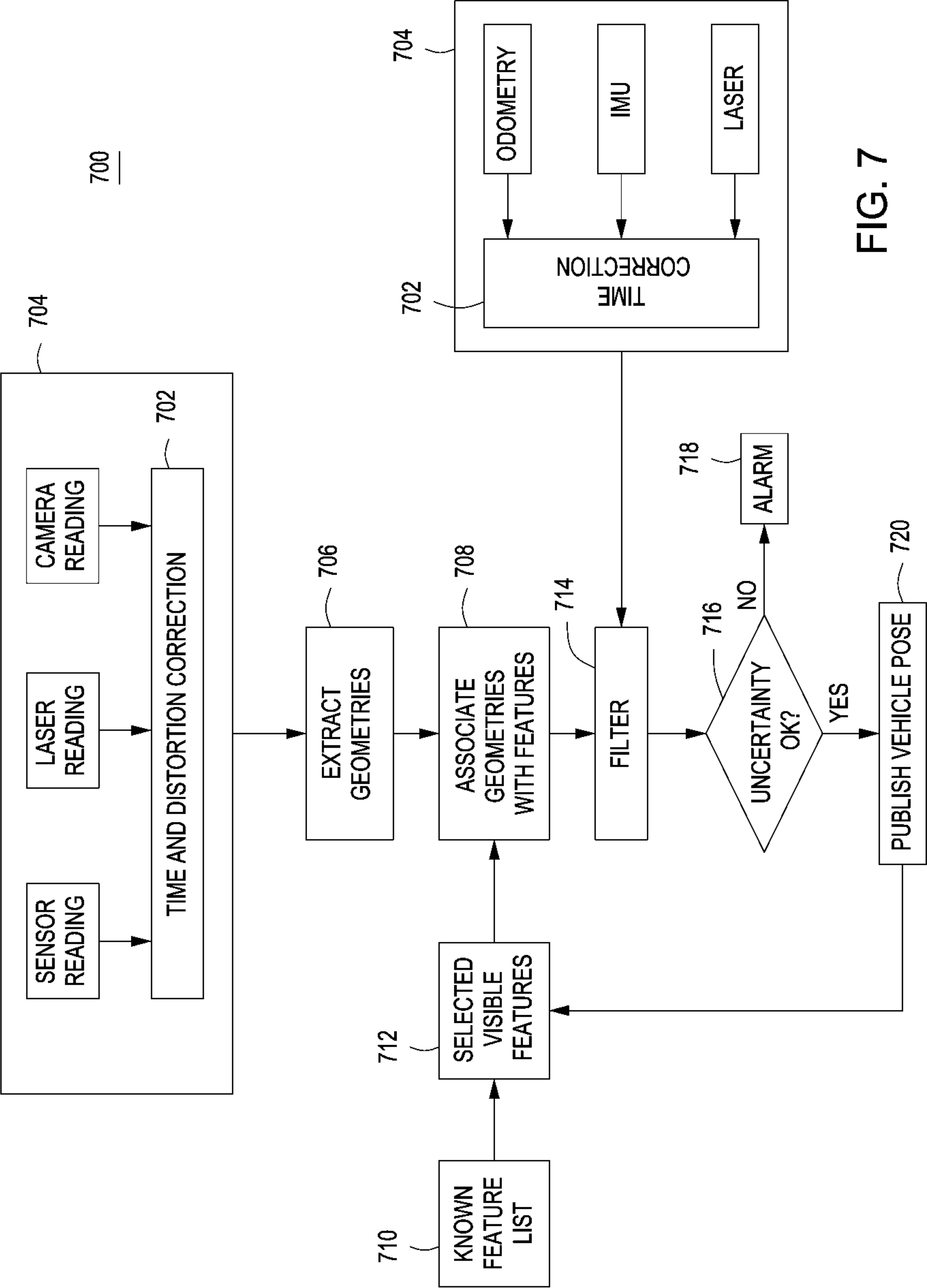


FIG. 7

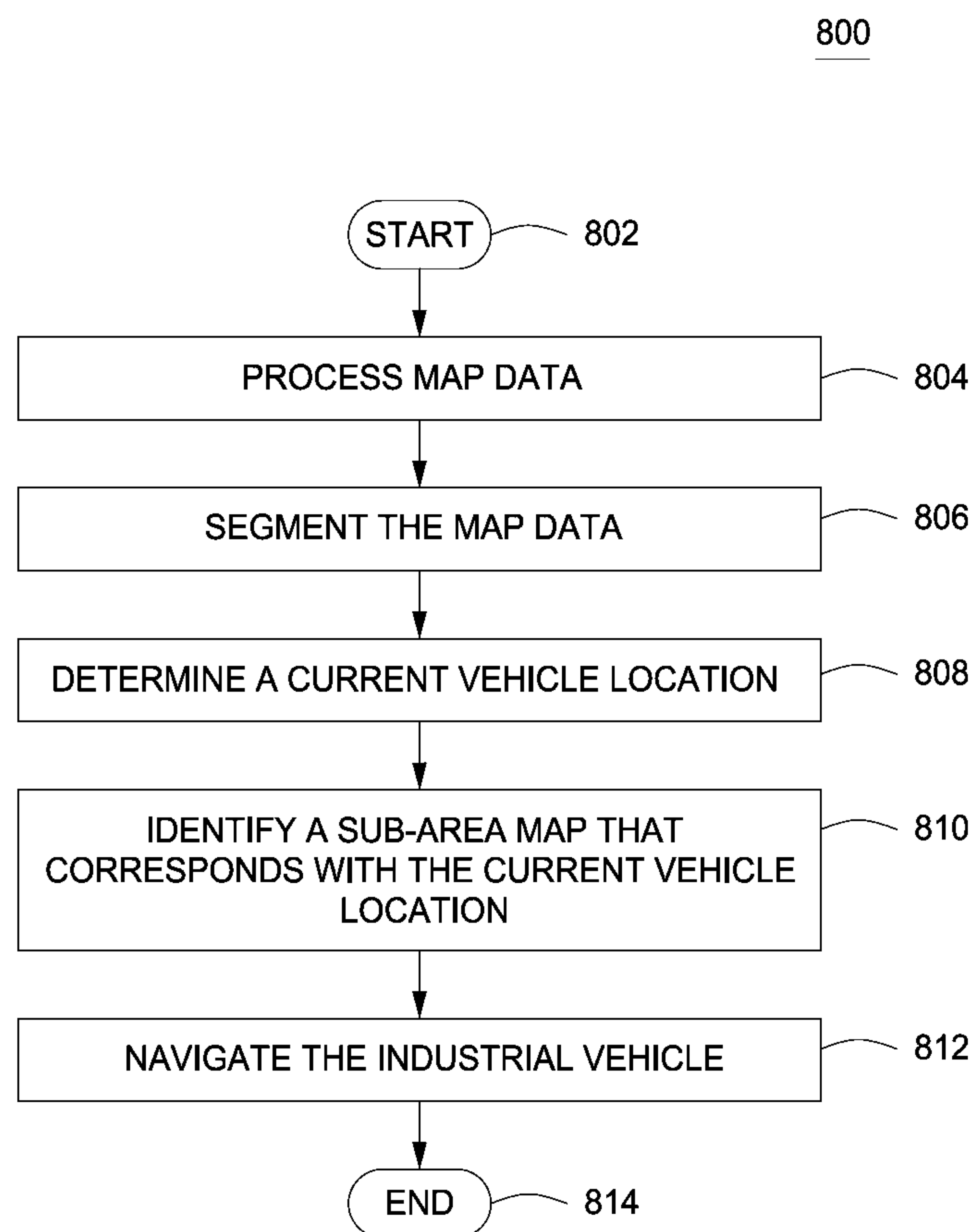


FIG. 8

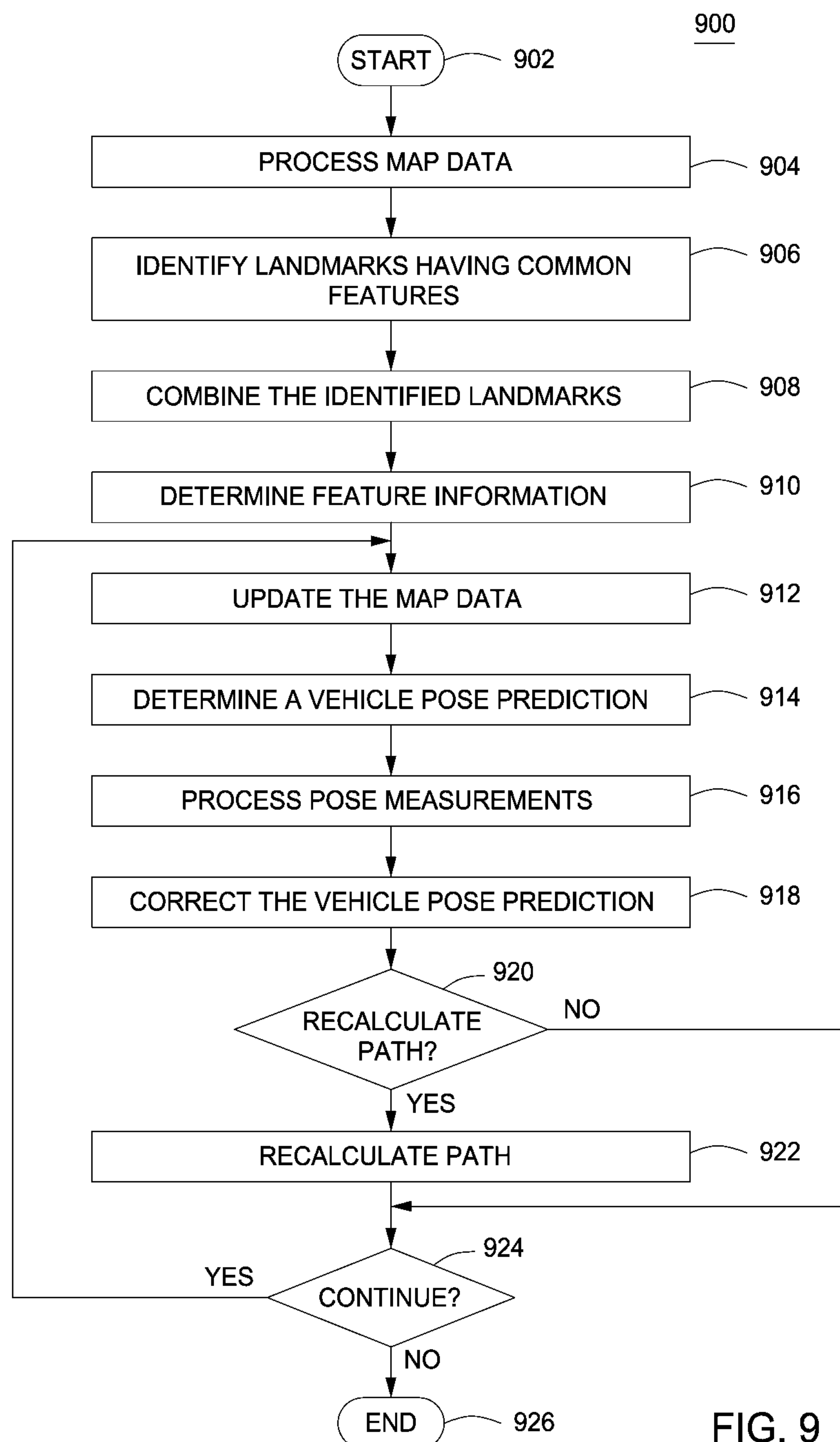


FIG. 9

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METHOD AND APPARATUS FOR FACILITATING MAP DATA PROCESSING FOR INDUSTRIAL VEHICLE NAVIGATION

BACKGROUND

1. Technical Field

Embodiments of the present invention generally relate to environment based navigation systems for industrial vehicles and, more particular, to a method and apparatus for facilitating map data processing for industrial vehicle navigation.

2. Description of the Related Art

Entities regularly operate numerous facilities in order to meet supply and/or demand goals. For example, small to large corporations, government organizations and/or the like employ a variety of logistics management and inventory management paradigms to move objects (e.g., raw materials, goods, machines and/or the like) into a variety of physical environments (e.g., warehouses, cold rooms, factories, plants, stores and/or the like). A multinational company may build warehouses in one country to store raw materials for manufacture into goods, which are housed in a warehouse in another country for distribution into local retail markets. The warehouses must be well-organized in order to maintain and/or improve production and sales. If raw materials are not transported to the factory at an optimal rate, fewer goods are manufactured. As a result, revenue is not generated for the unmanufactured goods to counterbalance the costs of the raw materials.

Unfortunately, physical environments, such as warehouses, have several limitations that prevent timely completion of various tasks. Warehouses and other shared use spaces, for instance, must be safe for a human work force. Some employees operate heavy machinery and industrial vehicles, such as forklifts, which have the potential to cause severe or deadly injury. Nonetheless, human beings are required to use the industrial vehicles to complete tasks, which include object handling tasks, such as moving pallets of goods to different locations within a warehouse. Most warehouses employ a large number of forklift drivers and forklifts to move objects. In order to increase productivity, these warehouses simply add more forklifts and forklift drivers.

Some warehouses utilize equipment for automating these tasks. As an example, these warehouses may employ automated industrial vehicles, such as forklifts, to carry objects on paths and then, unload these objects onto designated locations. When navigating an industrial vehicle, it is necessary to process map data efficiently and quickly in order to formulate these paths. If the industrial vehicle must compare sensor measurements with feature information associated with each and every landmark to compute the vehicle position, the time required to perform the computations requires the industrial vehicle to move slowly and ineffectively. A drawback of an Extended Kalman filter (EKF) approach is that dynamically added landmarks impose an immense computational cost on localization and mapping. To provide accurate localization information in real time, a number of dynamic landmarks being managed by the EKF at any time are minimized.

Therefore, there is a need in the art for a method and apparatus for facilitating map data processing for industrial vehicle navigation by reducing a number of features to process and/or store to perform vehicle localization.

SUMMARY

Various embodiments of the present invention generally include a method and apparatus for facilitating map data

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processing for industrial vehicle navigation. In one embodiment, the method of partitioning map data for industrial vehicle navigation includes segmenting map data associated with a physical environment into a plurality of sub-area maps, identifying a sub-area map that corresponds with a current vehicle location and navigating an industrial vehicle using the identified sub-area map.

BRIEF DESCRIPTION OF THE DRAWINGS

So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

FIG. 1 is a perspective view of a physical environment comprising various embodiments of the present disclosure;

FIG. 2 illustrates a perspective view of the forklift for navigating a physical environment to perform various tasks according to one or more embodiments;

FIG. 3 is a structural block diagram of a system for providing accurate localization for an industrial vehicle according to one or more embodiments

FIG. 4 is a functional block diagram of a system for providing accurate localization for an industrial vehicle according to one or more embodiments;

FIG. 5 is an interaction diagram illustrating a localization and mapping process for an industrial vehicle according to one or more embodiments;

FIG. 6 is a schematic illustration of a map for estimating a position for the industrial vehicle according to one or more embodiments;

FIG. 7 is a functional block diagram illustrating a localization and mapping process for navigating an industrial vehicle according to one or more embodiments;

FIG. 8 is a flow diagram of a method for partitioning map data into sub-area maps according to one or more embodiments; and

FIG. 9 is a flow diagram of a method for facilitating map data processing according to one or more embodiments.

DETAILED DESCRIPTION

FIG. 1 illustrates a schematic, perspective view of a physical environment **100** comprising one or more embodiments of the present invention.

In some embodiments, the physical environment **100** includes a vehicle **102** that is coupled to a mobile computer **104**, a central computer **106** as well as a sensor array **108**. The sensor array **108** includes a plurality of devices for analyzing various objects within the physical environment **100** and transmitting data (e.g., image data, video data, map data, three-dimensional graph data and/or the like) to the mobile computer **104** and/or the central computer **106**, as explained further below. The sensor array **108** includes various types of sensors, such as encoders, ultrasonic range finders, laser range finders, pressure transducers and/or the like.

The physical environment **100** further includes a floor **110** supporting a plurality of objects. The plurality of objects include a plurality of pallets **112**, a plurality of units **114** and/or the like as explained further below. The physical environment **100** also includes various obstructions (not pictured) to the proper operation of the vehicle **102**. Some of the plu-

ality of objects may constitute obstructions along various paths (e.g., pre-programmed or dynamically computed routes) if such objects disrupt task completion. For example, an obstacle includes a broken pallet at a target destination associated with an object load being transported. The physical environment **100** also includes a plurality of markers **116**. The plurality of markers **116** are illustrated as objects attached to a ceiling. In some embodiments, the markers **116** may be located on the floor or a combination of the floor and ceiling. In some embodiments, the plurality of markers **116** are beacons that facilitate environment based navigation as explained further below. The plurality of markers **116** as well as other objects around the physical environment **100** form landmarks defined by environmental features. The mobile computer **104** extracts the environment features and determines an accurate, current vehicle pose.

The physical environment **100** may include a warehouse or cold store for housing the plurality of units **114** in preparation for future transportation. Warehouses may include loading docks to load and unload the plurality of units from commercial vehicles, railways, airports and/or seaports. The plurality of units **114** generally include various goods, products and/or raw materials and/or the like. For example, the plurality of units **114** may be consumer goods that are placed on ISO standard pallets and loaded into pallet racks by forklifts to be distributed to retail stores. The vehicle **102** facilitates such a distribution by moving the consumer goods to designated locations where commercial vehicles (e.g., trucks) load and subsequently deliver the consumer goods to one or more target destinations.

According to one or more embodiments, the vehicle **102** may be an automated guided vehicle (AGV), such as an automated forklift, which is configured to handle and/or move the plurality of units **114** about the floor **110**. The vehicle **102** utilizes one or more lifting elements, such as forks, to lift one or more units **114** and then, transport these units **114** along a path within a transit area **120** (e.g., corridor) to be placed at a slot area **122**. Alternatively, the one or more units **114** may be arranged on a pallet **112** of which the vehicle **102** lifts and moves to the designated location.

Each of the plurality of pallets **112** is a flat transport structure that supports goods in a stable fashion while being lifted by the vehicle **102** and/or another jacking device (e.g., a pallet jack and/or a front loader). The pallet **112** is the structural foundation of an object load and permits handling and storage efficiencies. Various ones of the plurality of pallets **112** may be utilized within a rack system (not pictured). Within a certain rack system, gravity rollers or tracks allow one or more units **114** on one or more pallets **112** to flow to the front. The one or more pallets **112** move forward until slowed or stopped by a retarding device, a physical stop or another pallet **112**.

In some embodiments, the mobile computer **104** and the central computer **106** are computing devices that control the vehicle **102** and perform various tasks within the physical environment **100**. The mobile computer **104** is adapted to couple with the vehicle **102** as illustrated. The mobile computer **104** may also receive and aggregate data (e.g., laser scanner data, image data and/or any other related sensor data) that is transmitted by the sensor array **108**. Various software modules within the mobile computer **104** control operation of hardware components associated with the vehicle **102** as explained further below.

The physical environment **100** may be characterized as a dynamic shared use area in which pallets are expected to be placed on the floor **110** at known locations. Both the mobile computer **104** and/or central computer **106** perform dynamic

mapping of the physical environment **100** at run time to maintain an up-to-date global map of the physical environment. In some embodiments, the central computer **104** segments a global map into smaller sub-area maps and sends the sub-area maps to the vehicles. In this manner, the mobile computer **104** has less features of landmarks to process at any given time, e.g., only processing landmarks which are either in a sub-area map in which the industrial vehicle **102** currently operates or are visible to the industrial vehicle **102** at its current position or a combination of both. In other embodiments, the global map is stored by the mobile computer **104** and the mobile computer **104** uses only a sub-area map extracted from the global map to navigate. Once the industrial vehicle **102** approaches a new sub-area, the central computer **104** sends a corresponding sub-area map, or the mobile computer **104** extracts a corresponding sub-area map from its locally stored global map. The mobile computer **104** may also update the corresponding sub-area map with feature information that is communicated by at least one second industrial vehicle **102**.

FIG. 2 illustrates a perspective view of the forklift **200** for facilitating automation of various tasks within a physical environment according to one or more embodiments of the present invention.

The forklift **200** (i.e., a lift truck, a high/low, a stacker-truck, trailer loader, sideloader or a fork hoist) is a powered industrial truck having various load capacities and used to lift and transport various objects. In some embodiments, the forklift **200** is configured to move one or more pallets (e.g., the pallets **112** of FIG. 1) of units (e.g., the units **114** of FIG. 1) along paths within the physical environment (e.g., the physical environment **100** of FIG. 1). The paths may be pre-defined or dynamically computed as tasks are received. The forklift **200** may travel inside a storage bay that is multiple pallet positions deep to place or retrieve a pallet. Oftentimes, the forklift **200** is guided into the storage bay and places the pallet on cantilevered arms or rails. Hence, the dimensions of the forklift **200**, including overall width and mast width, must be accurate when determining an orientation associated with an object and/or a target destination.

The forklift **200** typically includes two or more forks (i.e., skids or tines) for lifting and carrying units within the physical environment. Alternatively, instead of the two or more forks, the forklift **200** may include one or more metal poles (not pictured) in order to lift certain units (e.g., carpet rolls, metal coils and/or the like). In one embodiment, the forklift **200** includes hydraulics-powered, telescopic forks that permit two or more pallets to be placed behind each other without an aisle between these pallets.

The forklift **200** may further include various mechanical, hydraulic and/or electrically operated actuators according to one or more embodiments. In some embodiments, the forklift **200** includes one or more hydraulic actuator (not labeled) that permit lateral and/or rotational movement of two or more forks. In one embodiment, the forklift **200** includes a hydraulic actuator (not labeled) for moving the forks together and apart. In another embodiment, the forklift **200** includes a mechanical or hydraulic component for squeezing a unit (e.g., barrels, kegs, paper rolls and/or the like) to be transported.

The forklift **200** may be coupled with the mobile computer **104**, which includes software modules for operating the forklift **200** in accordance with one or more tasks. The forklift **200** is also coupled with an array comprising various sensor devices (e.g., the sensor array **108** of FIG. 1), which transmits sensor data (e.g., image data, video data, range map data and/or three-dimensional graph data) to the mobile computer **104** for extracting information associated with environmental

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features. These devices may be mounted to the forklift **200** at any exterior and/or interior position or mounted at known locations around the physical environment **100**. Exemplary embodiments of the forklift **200** typically includes a camera **202**, a planar laser scanner **204** attached to each side and/or an encoder **206** attached to each wheel **208**. In other embodiments, the forklift **200** includes only the planar laser scanner **204** and the encoder **206**. The forklift **200** may use any sensor array with a field of view that extends to a current direction of motion (e.g., travel forwards, backwards, fork motion up/down, reach out/in and/or the like). These encoders determine motion data related to vehicle movement. Externally mounted sensors may include laser scanners or cameras positioned where the rich data set available from such sensors would enhance automated operations. External sensors may include a limited set transponders and/or other active or passive means by which an automated vehicle could obtain an approximate position to see a localization function.

In some embodiments, a number of sensor devices (e.g., laser scanners, laser range finders, encoders, pressure transducers and/or the like) as well as their position on the forklift **200** are vehicle dependent, and the position at which these sensors are mounted affects the processing of the measurement data. For example, by ensuring that all of the laser scanners are placed at a measurable position, the sensor array **108** may process the laser scan data and transpose it to a center point for the forklift **200**. Furthermore, the sensor array **108** may combine multiple laser scans into a single virtual laser scan, which may be used by various software modules to control the forklift **200**.

FIG. **3** is a structural block diagram of a system **300** for providing accurate localization for an industrial vehicle according to one or more embodiments. In some embodiments, the system **300** includes the mobile computer **104**, the central computer **106** and the sensor array **108** in which each component is coupled to each other through a network **302**.

The mobile computer **104** is a type of computing device (e.g., a laptop, a desktop, a Personal Digital Assistant (PDA) and the like) that comprises a central processing unit (CPU) **304**, various support circuits **306** and a memory **308**. The CPU **304** may comprise one or more commercially available microprocessors or microcontrollers that facilitate data processing and storage. Various support circuits **306** facilitate operation of the CPU **304** and may include clock circuits, buses, power supplies, input/output circuits and/or the like. The memory **308** includes a read only memory, random access memory, disk drive storage, optical storage, removable storage, and the like. The memory **308** includes various data, such as map data **310**, a plurality of sub-area maps **312**, feature information **314**, pose measurement data **316**, a vehicle heading **317**, pose prediction data **318** and a path **319**. The memory **308** includes various software packages, such as an environment based navigation module **420**.

The central computer **106** is a type of computing device (e.g., a laptop computer, a desktop computer, a Personal Digital Assistant (PDA) and the like) that comprises a central processing unit (CPU) **322**, various support circuits **324** and a memory **326**. The CPU **322** may comprise one or more commercially available microprocessors or microcontrollers that facilitate data processing and storage. Various support circuits **324** facilitate operation of the CPU **322** and may include clock circuits, buses, power supplies, input/output circuits and/or the like. The memory **326** includes a read only memory, random access memory, disk drive storage, optical storage, removable storage, and the like. The memory **326** includes various software packages, such as a mapping module **328**, as well as various data, such as a task **430**. Optionally,

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the memory **326** stores a copy of global map data **310** (representing a global map) and/or the sub-area maps **312**.

The network **302** comprises a communication system that connects computing devices by wire, cable, fiber optic, and/or wireless links facilitated by various types of well-known network elements, such as hubs, switches, routers, and the like. The network **302** may employ various well-known protocols to communicate information amongst the network resources. For example, the network **302** may be part of the Internet or intranet using various communications infrastructure such as Ethernet, WiFi, WiMax, General Packet Radio Service (GPRS), and the like.

The sensor array **108** is communicably coupled to the mobile computer **104**, which is attached to an automated vehicle, such as a forklift (e.g., the forklift **200** of FIG. **2**). The sensor array **108** includes a plurality of devices **322** for monitoring a physical environment and capturing various data, which is stored by the mobile computer **104** as the sensor input messages **312**. In some embodiments, the sensor array **108** may include any combination of one or more laser scanners and/or one or more cameras. In some embodiments, the plurality of devices **332** may be mounted to the automated vehicle. For example, a laser scanner and a camera may be attached to a lift carriage at a position above the forks. Alternatively, the laser scanner and the camera may be located below the forks. The plurality of devices **332** may also be distributed throughout the physical environment at fixed positions.

In some embodiments, the global map data **310** includes dynamic features and/or static features of a physical environment, such as a shared use area for human workers and automated industrial vehicles. The global map data **310** comprises feature information **340** and landmark data **342** (as is illustrated in FIG. **3**). In one embodiment, the feature information includes a dynamic and/or static features representing a physical environment proximate the vehicle, such as a shared use area for human workers and automated industrial vehicles. Static features represent objects that do not change within the environment, e.g., walls, storage racks, and the like. The map data **310** may be organized to form a vector of known landmarks, static and dynamic features. In some embodiments feature information **340** include: feature geometry (line, corner, arc, etc.); a feature pose in global coordinate system; and a feature pose uncertainty. Typically, the pose uncertainty for static features is zero.

In some embodiments dynamic features represent objects that change within the environment, e.g. temporary obstructions such as broken pallets, objects to be stored, and the like. These features are likely to be stationary for a sufficient amount of time for the system to use them as localization map features. The system does not contain a-priori information about the pose of these features and thus the pose of these dynamic features can only be inferred by superimposing the vehicle centric measurement from sensors onto the estimated pose of the vehicle with respect to the global coordinate system. Because of the noise in sensor data, as well as the uncertainty in the vehicle pose estimation, all dynamic features have a pose uncertainty associated with their pose.

The physical environment may be segmented into a plurality of sub-areas with corresponding map data stored in the plurality of sub-area maps **312**. The feature information **314** defines features (e.g., curves, lines and/or the like) associated with various landmarks. These landmarks may be pre-defined and identified in a static map of the physical environment. The map module **328** may designate one or more objects (i.e.,

unloaded objects, such as a product item or pallet) as unique landmarks that correspond to specific sub-areas, such as a room in a warehouse

In some embodiments, the pose prediction data **318** includes an estimate of vehicle position and/or orientation of which the present disclosure may refer to as the vehicle pose prediction. The environment based navigation module **320** may produce such an estimate using a prior vehicle pose in addition to a vehicle motion model. The environment based navigation module **320** may also use a process filter to estimate uncertainty and/or noise for an upcoming vehicle pose prediction and update steps. After examining the map data **310** or a particular one of the sub-area maps **312**, the environment based navigation module **320** determines an estimate of a current vehicle position. The uncertainty in a vehicle pose creates an uncertainty in the position of observed features. The pose uncertainty in the feature information **312** is derived from a combination of vehicle position uncertainty and sensor noise.

In some embodiments, the environment based navigation module **320** includes processor-executable instructions for performing localization and mapping for an industrial vehicle. The environment based navigation module **320** reduces a number of known (landmark) features to compare with the feature information **314** by eliminating portions of the map data **310** from being processed during the localization. By partitioning the map data **310** into sub-area maps **312**, a number of static and/or dynamic landmarks being processed at any given time are limited to the number of landmarks in a particular sub-area map in which the industrial vehicle currently operates. Once location of the industrial vehicle, as determined by the environment based navigation module, leaves the particular sub-area the EBN module **320** selects a new sub-area map **312**. The module **320** may request a sub-area map **312** from the central computer, or the central computer **106** may automatically send a new sub-area map as the vehicle approaches the edge of a prior sub-area map. In an alternative embodiment, the EBN module may contain a mobile map module **344** that extracts a sub-area map **312** from the locally stored map data **310**. In either event, a map module **328/344** (global or mobile) constructs a new sub-area map **312** that corresponds with a portion of the physical environment required by the vehicle to navigate in the new location. Accordingly, the environment based navigation module **320** only uses known features associated with the new sub-area map **312**. In some embodiments, the environment based navigation module **320** updates the map data **310** with new dynamic features.

FIG. 4 is a functional block diagram of a system **400** for providing accurate localization for an industrial vehicle according to one or more embodiments. The system **400** includes the mobile computer **104**, which couples to an industrial vehicle, such as a forklift, as well as the sensor array **108**. Various software modules within the mobile computer **104** collectively form an environment based navigation module (e.g., the environment based navigation module **320** of FIG. 3).

The mobile computer **104** includes various software modules (i.e., components) for performing navigational functions, such as a localization module **402**, a mapping module **404**, a correction module **408**, and a vehicle controller **410**. The mobile computer **104** provides accurate localization for the industrial vehicle and updates map data **406** with information associated with environmental features. The localization module **402** also includes various components, such as a filter **414** and a feature extraction module **416** for determining a vehicle state **418**. The map module **404** includes various

data, such as dynamic features **422** and static features **424**. The map module **404** also includes various components, such as a feature selection module **420**.

In some embodiments, the sensor data is corrected in correction module **408** to correct for temporal and/or spatial distortion. The localization module **402** processes the corrected data and extracts features from the sensor data using feature extraction component **416**. These features are matched with the features from map module **404**, with the feature pose uncertainty and observation noise taken into account, and vehicle state **418** is then adjusted by the filter **414**. The vehicle pose **418**, which is modeled by the filter **414**, refers to a current vehicle state and includes data (e.g., coordinates) that indicate vehicle position, orientation, velocity, acceleration and the like. The localization module **402** communicates data associated with the vehicle pose **418** to the mapping module **404** while also communicating such data to the vehicle controller **410**. Based on the vehicle position and orientation, the vehicle controller **410** navigates the industrial vehicle to a destination.

In addition to the filter **414** for calculating the vehicle pose **418**, the localization module **414** also includes the feature extraction module **416** for extracting standard features from the corrected sensor data. The map module **404** compares the vehicle pose **418** with the static features **424** and dynamic features **422** to reduce a number of features to examine by eliminating features not currently visible from the features. In some embodiments, the map module **404** partitions the map data **406** into a plurality of maps that correspond with specific sub-areas of the physical environment. The feature selection module **420** manages addition and modification of the dynamic features **422** to the map data **406**. The feature selection module **420** can update the map data **406** to indicate areas recently occupied or cleared of certain features, such as known placed and picked items.

It is appreciated that the system **400** may employ several computing devices to perform environment based navigation. Any of the software modules within the computing device **104** may be deployed on different or multiple physical hardware components, such as other computing devices. The mapping module **404**, for instance, may be executed on a server computer (e.g., the central computer **102** of FIG. 1) over a network (e.g., the network **302** of FIG. 4) to connect with multiple mobile computing devices for the purpose of sharing and updating the map data **406** with a current vehicle position and orientation.

In some embodiments, the correction module **402** processes sensor input messages from disparate data sources, such as the sensor array **108**, having different sample/publish rates for the vehicle pose **418** as well as different (internal) system delays. The correction module **402** extracts observed pose measurements from the sensor data within these messages. The correction module **402** examines each message separately in order to preserve the consistency of each observation.

FIG. 5 is an interaction diagram illustrating a localization and mapping process **500** for an industrial vehicle according to one or more embodiments. Specifically, the localization and mapping process **500** includes processing and communicating various data between components or layers **502**, such as sensor data correction **504**, an interface **506**, feature extraction **508**, data association **510**, EKF **512** and dynamic map **514**. The localization and mapping process **500** supports industrial vehicle operation using primarily environmental features. The interface **506** facilitates control over the layers **502** and is added to an environment based navigation module.

The feature extraction **508** examines data inputted by sensor devices and extracts observed features (e.g. lines and corners). The data association **510** compares the observed features with known feature information to identify matching features with existing static and/or dynamic map data. The EKF **512** is an extended Kalman Filter that, given measurements associated with the matching features and a previous vehicle pose, provides a most likely current vehicle pose. The dynamic map manager **514** maintains an up-to-date dynamic map of features used for localization that are not found in a-priori static map.

FIG. **6** is a schematic illustration of a map **600** for estimating a position for the industrial vehicle **102** according to one or more embodiments. Various software modules stored within a computer coupled to the industrial vehicle **102** execute the position estimation **600**. The industrial vehicle **102** uses various sensor devices (e.g., the plurality of sensor devices **332** of FIG. **3**) to sense objects within a visibility range **602**. Specifically, the visibility range **602** may refer to a laser range that is formed by laser scanners. As explained further below, the industrial vehicle senses landmarks **604** whose features are used to form grid lines **606** for estimating the the pose of an industrial vehicle according to some embodiments. Furthermore, the landmarks **604** combine to form an infrastructure unit **608**.

Physical environments, such as a warehouse, include landmarks having related features, which can be extracted to facilitate localization and mapping. Examples of related features include the rack legs of high density racking where the set of legs form an infrastructure unit **608**. Data associated with the infrastructure unit such as the virtual line, or gridline **606**, that joins each and every leg in a racking bay may be used to assist localization. In this case, the virtual feature may be treated by the localization module (the localization module **402** of FIG. **4**) equivalent to a virtual wall. In the case where the vehicle **102** is moving in an aisle between two sets of racking there are two grid-lines **606** which together form an aisle. Those skilled in the art can readily see that extracting virtual features from known attributes of physical features can help overcome problems in warehouse area where usual localization landmarks such as walls and corners are not visible from sensors during majority of time in operation.

Using the laser scanners, a mobile computer (e.g., the mobile computer **104** of FIG. **1**) coupled to the industrial vehicle **102** identifies racking legs, which are stored as landmarks **604**. Common features amongst the racking legs indicate that these landmarks **604** are related. For example, each racking leg is similar or identical in size, shape and orientation to each other. The industrial vehicle **102** fits lines to these racking legs to provide gridlines **606** to correct a vehicle pose. When executing a task within racking aisles, walls are generally not within the range **602**. Therefore, either these gridlines **606**, or an aisle defined by both sets of parallel gridlines **606**, can be used to adjust the vehicle position and heading. The gridline **606** and aisle is stored as a virtual feature in the map which is associated with the racking legs.

FIG. **7** is a functional block diagram illustrating a localization and mapping process **700** for navigating an industrial vehicle according to one or more embodiments. As sensor data is provided by a plurality of sensor devices **704**, a time and distortion correction module **702** rearranges sensor input messages based on acquisition time. A geometry extract module **706** examines the corrected sensor data identifies candidate geometries from the sensor corrected sensor data. In some embodiments the known standard features **710** are selected using the current vehicle pose **712**. The selection may be performed according to a specific sub-area of the

physical environment, a sensor visibility constraint (e.g. the sensor range **602** of FIG. **6**) or other selection criteria that are well known in the art. The geometries from the sensor data are associated with the features **708** as the resulting identified features list presented to the filter **714**. Accordingly, such a reduction in a number of features to process enhances feature association data processing and filter data processing by limiting the number of features to be processed. Using the feature list and the corrected odometry sensor data, the filter **714** updates a pose prediction/estimation as well as map data.

Generally, the filter **714** provides real time positioning information (localization) for an automated industrial vehicle or manually driven vehicle. The filter **714** also helps provide data indicating uncertainty associated with the vehicle pose measurements. Thus, should the industrial vehicle temporarily travel in an empty space without available features or other environmental markers, the filter **714** continues to provide accurate localization by updating the vehicle pose along with determining indicia of uncertainty. Depending on safety requirements, the industrial vehicle may operate within a defined degree of uncertainty before an error triggers the alarm **718**.

During the time and distortion correction step, the module **704** receives readings (i.e., observations) taken from each sensor device. These readings may be provided by a laser and/or camera or any other type of sensor device for extracting environment features. The time and distortion correction step **702** also corrects for any distortion that may be due to finite measurement time and the speed of travel of the industrial vehicle. This distortion occurs as the industrial vehicle and sensors are moving (e.g., during a scan), which associates a temporal characteristic with the data. The module **706** extracts various environment features from the sensor data, such as a line, corner, arc, or marker, which are provided in a standard geometry format for data association **708**. Pose measurements from the sensor devices **704** provide a relative change in position, velocity, or acceleration. These measurements are used to update the estimated pose of the industrial vehicle. The known feature list **710** includes a map of a physical environment. The data association **708** compares a subset of the known feature list **710** provided by feature selection **712** with the extracted standard geometries in order to estimate vehicle position.

In some embodiments, the vehicle pose include x-y coordinates associated with the vehicle position as well as a vehicle heading. The odometry data provides gives a linear velocity and a rotational velocity. The linear velocity refers to the velocity of the wheel upon which an encoder or velocity measurement device is installed. The rotational velocity indicates how much the heading of the vehicle has changed with respect to the global coordinate system and the vehicle. The filter **714** corrects the vehicle pose by eliminating process noise (i.e., odometry noise) by modeling wheel slip (proportional to linear velocity) and angular slip (proportional to angular velocity).

FIG. **8** is a flow diagram of a method for partitioning map data into sub-area maps according to one or more embodiments. In some embodiments, an environment based navigation module (e.g., the environment based navigation module **320** of FIG. **3**) or a mapping module (e.g., the mapping module **328** of FIG. **3**) performs each and every step of the method **800**. In other embodiments, some steps are omitted or skipped. The environment based navigation module is stored within a mobile computer (e.g., the mobile computer **104** of FIG. **1**) that is operably coupled to an industrial vehicle (e.g., the industrial vehicle **102** of FIG. **1**). The map module is stored within a central computer or mobile computer (e.g., the

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central computer **106** or mobile computer **104** of FIG. **1**) that communicates with the industrial vehicle as well as one or more second industrial vehicles. When performing a task (e.g., the task **330** of FIG. **3**), the central computer instructs the mobile computer to navigate the industrial vehicle along a particular path (e.g., the path **319** of FIG. **3**). The method **800** starts at step **802** and proceeds to step **804**.

At step **804**, the method **800** processes map data (e.g., the map data **310** of FIG. **3**). In some embodiments, the environment based navigation module examines the map data in order to localize the industrial vehicle. Before following the path, the environment based navigation must determine an accurate vehicle pose. The map module may optionally communicate map data (e.g., the map data **310** of FIG. **3**) to the mobile computer. Such map data may be a global map of an entire physical environment (e.g., the physical environment **100** of FIG. **1**) or a sub-area map.

At step **806**, the method **800** segments the map data into a plurality of sub-area maps. Each sub-area map may be associated with a certain portion of the physical environment, such as a specific room of a warehouse. In order to perform the partition of the map data, the method **800** uses feature information associated with the physical environment. The method **800** defines a sub-area map based on vehicle pose and other available information such as the planned path for the vehicle. These sub-area maps contains a subset of landmarks expected to be seen by the vehicle given its pose and, for example, planned path. These landmarks may include static, dynamic, and/or virtual features.

At step **808**, the method **800** determines a current vehicle location. In some embodiments, the method **800** accesses the map data and extracts a vehicle pose (e.g., the vehicle pose **318**) that includes the current vehicle location. At step **810**, the method **800** generates a sub-area map that corresponds with the current vehicle location. The sub-area map includes feature information for a sub-area of the physical environment that would be likely to be observed by the industrial vehicle.

At step **812**, the method **800** navigates the industrial vehicle using the identified sub-area map. The environment based navigation module directly controls vehicle operations and navigates the industrial vehicle along the path according to some embodiments. When the industrial vehicle leaves the sub-area, the method **800** identifies another sub-area map that corresponds with a new vehicle location. In some embodiments, the environment based navigation module requests the other sub-area map from the map module and the map module creates the sub-area map upon request. In other embodiments, the map module selects the other sub-area map from the plurality of sub-area maps.

In one embodiment, the sub-area maps are generated (or selected) as a sequence. Each map is provided by the map module prior to the vehicle reaching the edge of the current map. The maps generally overlap in coverage such that a gap in map information is not created as the vehicle moves from one sub-area map coverage to the next.

At step **814**, the method **800** ends.

FIG. **9** is a flow diagram of a method **900** for facilitating map data processing according to one or more embodiments. In some embodiments, an environment based navigation module (e.g., the environment based navigation module **320** of FIG. **3**) or a mapping module (e.g., the map module **328/344** of FIG. **3**) performs each and every step of the method **900**. In other embodiments, some steps are omitted or skipped. The environment based navigation module is stored within a mobile computer (e.g., the mobile computer **104** of FIG. **1**) that is operably coupled to an industrial vehicle (e.g.,

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the industrial vehicle **102** of FIG. **1**). The map module is stored within a central computer or the mobile computer that communicates with the industrial vehicle as well as one or more second industrial vehicles. When performing a task (e.g., the task **430** of FIG. **3**), the central computer instructs the mobile computer to navigate the industrial vehicle along a particular path (e.g., the path **319** of FIG. **3**).

The method **900** starts at step **902** and proceeds to step **904**. At step **904**, the method **900** processes map data by selecting a subset of features from the map that are likely to be observed by the industrial vehicle. Processing the map data will reduce the number and landmarks and consequently features to be processed by the industrial vehicle to those in the proximate area of the industrial vehicle. At step **906**, the method **900** identifies landmarks that have common features to which virtual landmarks may be mapped. These landmarks may include static (e.g. racking legs), dynamic (e.g. pallets placed during system operation). At step **908** the identified landmarks are mapped to the virtual landmarks stored in the map (e.g. the aisle formed by rows of racking system). At step **910** all landmarks are expanded into features that may be detected by the sensor array **108** associated with an industrial vehicle. These features may be geometric representation of the physical landmarks, such as lines and arcs.

At step **912**, the method **900** updates the map data with the selected feature information. In some embodiments, the method **900** fits the feature information with known feature information for the infrastructure unit. For example, the method **900** compares the feature information with known dimension data for the racking system. At step **914**, the method **900** determines a vehicle pose prediction according to odometry sensor data (e.g., pose prediction data **318** of FIG. **3**). In some embodiments, the method **900** examines a previous vehicle pose and predicts a new vehicle pose after a time interval. At step **916**, the method **900** processes pose measurements. At step **918**, the method **900** corrects the vehicle pose prediction. After sensing pose measurement data (e.g., the pose measurement data **316** of FIG. **3**) related to one or more landmarks, the method **900** updates the vehicle pose prediction to produce an accurate vehicle pose.

At step **920**, the method **900** determines whether the change to the map requires the vehicle to recalculate a path in order to complete the task (e.g., the path **319** of FIG. **3**). If the method **900** decides to recalculate the path, the method **900** proceeds to step **922**. If, on the other hand, the method **900** decides not to update the path, the method **900** proceeds to step **924**. At step **922**, the method **900** recalculates the path. At step **924**, the method **900** determines whether to continue performing localization and mapping for executing the task. If the method **900** decides to continue performing the localization and mapping, the method **900** returns to step **912**. If, on the other hand, the method **900** decides not to continue, the method **900** proceeds to step **926**. At step **926**, the method **900** ends.

Various elements, devices, and modules are described above in association with their respective functions. These elements, devices, and modules are considered means for performing their respective functions as described herein.

While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

The invention claimed is:

1. A method of partitioning map data for industrial vehicle navigation in a physical environment, wherein:

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the physical environment comprises static features representing objects that do not change within the physical environment and dynamic features representing objects that change within the physical environment;

the industrial vehicle comprises a mobile computer and a sensor array communicably coupled to the mobile computer;

the mobile computer comprises a central processing unit and a memory comprising an environment based navigation module, a feature selection module, map data representing static features within the physical environment, and a plurality of sub-area maps;

the sensor array comprises a plurality of devices mounted to the industrial vehicle for monitoring the physical environment and producing sensor data representing the physical environment; and

the method comprises

- segmenting the physical environment, as represented by the map data, into a plurality of sub-areas with corresponding map data stored in the plurality of sub-area maps,
- utilizing the environment based navigation module and environmental features extracted from the sensor data to determine a location of the industrial vehicle relative to a particular sub-area,
- utilizing the environment based navigation module to derive respective pose uncertainties associated with the dynamic features based upon data comprising noise in the sensor data and uncertainty in the determined location of the industrial vehicle;
- selecting a sub-area map for use by the environment based navigation module based on the determined location of the industrial vehicle,
- updating the selected sub-area map to include dynamic features within the particular sub-area corresponding to the selected sub-area map based on environmental features in the sensor data produced by the sensor array and the respective pose uncertainties associated with the dynamic features within the particular sub-area,
- utilizing the feature selection module to manage the addition of dynamic features to the sub-area map based on the respective pose uncertainties associated with the dynamic features,
- utilizing the environment based navigation module, the sensor data, and the updated sub-area map to determine an updated location of the industrial vehicle, and navigating the industrial vehicle using the updated sub-area map and the updated location of the industrial vehicle.

2. A method as claimed in claim 1 wherein the selected sub-area map is updated by using the feature selection module to eliminate features that are not currently visible within the sensor data.

3. A method as claimed in claim 1 wherein the selected sub-area map is updated by using the feature selection module to include only those features that are visible within the sensor data.

4. A method as claimed in claim 1 wherein the particular sub-area corresponds to an area of the physical environment within a field of view of the sensor array of the industrial vehicle.

5. A method as claimed in claim 1 wherein the method further comprises triggering an alarm when the uncertainty in the determined location of the industrial vehicle exceeds a defined degree of uncertainty.

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6. A method as claimed in claim 1 wherein the dynamic features are used to update the selected sub-area map by superimposing vehicle centric measurements from the sensor array devices onto an estimated pose of the industrial vehicle with respect to a global coordinate system.

7. A method as claimed in claim 6 wherein the estimated pose of the industrial vehicle refers to a current vehicle state and comprises position data, orientation data, and velocity data.

8. A method as claimed in claim 1 wherein the sensor array comprises a camera.

9. A method as claimed in claim 1 wherein the sub-area map is selected by requesting the sub-area map from the mobile computer.

10. A method as claimed in claim 1 wherein the sub-area map is selected automatically when the industrial vehicle approaches the edge of a prior sub-area map.

11. A method as claimed in claim 1 wherein the mobile computer is in communication with a second industrial vehicle and the selected sub-area map is updated to include feature information that is communicated by the second industrial vehicle.

12. A method as claimed in claim 1 wherein:

- the physical environment comprises a dynamic shared use area in which pallets are expected to be placed on a floor of the physical environment; and
- the dynamic features of the physical environment represent pallets placed on the floor of the physical environment.

13. A method as claimed in claim 12 wherein the feature selection module is further utilized to update map data to indicate areas recently occupied by or cleared of placed or picked items.

14. A method of partitioning map data for industrial vehicle navigation in a physical environment, wherein:

- the physical environment comprises a dynamic shared use area in which pallets are expected to be placed on a floor of the physical environment and comprises static features representing objects that do not change within the physical environment and dynamic features representing pallets placed on the floor of the physical environment;
- the industrial vehicle comprises a mobile computer and a sensor array communicably coupled to the mobile computer;
- the mobile computer comprises a central processing unit and a memory comprising an environment based navigation module, a feature selection module, map data representing static features within the physical environment, and a plurality of sub-area maps;
- the sensor array comprises a plurality of devices mounted to the industrial vehicle for monitoring the physical environment and producing sensor data representing the physical environment;
- the method comprises

- segmenting the physical environment, as represented by the map data, into a plurality of sub-areas with corresponding map data stored in the plurality of sub-area maps;
- utilizing the environment based navigation module and environmental features extracted from the sensor data to determine a location of the industrial vehicle relative to a particular sub-area;
- utilizing the environment based navigation module to derive respective pose uncertainties associated with the dynamic features based upon data comprising noise in the sensor data and uncertainty in the determined location of the industrial vehicle;

selecting a sub-area map for use by the environment
based navigation module based on the determined
location of the industrial vehicle;
updating the selected sub-area map to include dynamic
features within the particular sub-area corresponding 5
to the selected sub-area map based on environmental
features in the sensor data produced by the sensor
array and the respective pose uncertainties associated
with the dynamic features within the particular sub-
area, and by using the feature selection module to 10
eliminate dynamic features that are not currently vis-
ible within the sensor data;
utilizing the feature selection module to manage the
addition of dynamic features to the sub-area map
based on the respective pose uncertainties associated 15
with the dynamic features and to update map data to
indicate areas recently occupied by or cleared of
placed or picked items;
utilizing the environment based navigation module, the
sensor data, and the updated sub-area map to deter- 20
mine an updated location of the industrial vehicle; and
navigating the industrial vehicle using the updated sub-
area map and the updated location of the industrial
vehicle.

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